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Enhancing the assessment of critical resource use at the country level with the SCARCE method – Case study of Germany[☆]

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Abstract

The demand for many resources has increased significantly over the last decades due to their growing importance for industrial and technological development. Thus, various methods were developed to assess availability constraints of resources in relation to their vulnerability within countries and/or sectors (criticality). However, these methods display several short-comings. Thus, the aim of the introduced approach is, to enhance the assessment of critical resource use on country level with the SCARCE method, by considering the two dimensions criticality (with the sub dimensions availability and vulnerability) and societal acceptance (with the sub dimensions compliance with social standards and compliance with environmental standards). For five of the 12 introduced categories measuring availability constraints the country specific import mix is used to determine availability constraints of resources individually for the country under consideration. These results can further be compared with global constraints (which are calculated based on global production data) to determine if the country under consideration performs worse or better than the global average. To measure social aspects the categories small scale mining, geopolitical risk and human rights abuse are introduced. Environmental aspects are considered within the categories sensitivity of the local biodiversity, climate change and water scarcity. Additionally, next to metals also fossil fuels are included allowing a direct comparison of both abiotic resources. The SCARCE method is applied for the case study of Germany for which criticality results are presented and their plausibility is validated. It is shown that for Germany tungsten is the raw material showing high risks in all considered dimensions excluding the sub dimension vulnerability. Its high availability constraints are defined by the categories political stability, primary material use and price fluctuations. Further, due to the countries tungsten is imported from (e.g. Bolivia), its compliance with social and environmental standards is low. To enhance the applicability of the SCARCE method, indicator results are provided for 40 resources to assess their availability constraints as well as their compliance with social and environmental standards.

Keywords: *Resource use; Criticality; Availability constraints; Sustainable development*

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1 Introduction

In the last decades the demand of resources and raw materials rose significantly due to continuing global industrial and technological development. With that also awareness with regard to a sustainable use of resources and raw materials has grown as well, which is reflected in strategies and measures on international as well as national level (e. g. European Commission, 2011, European Commission, 2015; United Nations, 2016). This implies considering availability of resources and raw materials for current and future generations and the vulnerability of countries and/or sectors with regard to critical resources and raw materials (economic dimension) as well as the extraction, processing and use of resources and raw materials in line with ecological and societal considerations (environmental and social dimension). The term "resources" refers to entities, which can be extracted from nature and transferred to the anthroposphere. This includes abiotic and biotic resources, minerals, metals, fossil fuels as well as water, land, and the natural environment (Schneider et al., 2016; Sonderegger et al., 2017).

Methods to determine aspects with regard to resource use have been published manifold in the last years, considerably improving the assessment of resource use. They are addressing the micro (product), meso (company) and macro (company) level.

For the assessment of resource use on product level several approaches exist (e. g. Guinée et al., 1993, Graedel et al., 2012, VDI e.V. (2013), Schneider et al., 2013, Schneider et al., 2015, Dewulf et al., 2015, Bach et al., 2016 and Gemechu et al., 2016). Most of them complement the existing Life Cycle Assessment (LCA) methodology according to ISO 14040/44 (Finkbeiner et al., 2006). These approaches range from considering single aspects (e.g. depletion of abiotic resource (Guinée et al., 1993)) over multiple aspects (e.g. several socioeconomic availability constraints (Schneider et al., 2013)) to first approaches with regard to sustainability assessments (e.g. Bach et al., 2016). So far the focus has been on metals and minerals, with only few methodologies also considering biotic resources and raw materials (Oakdene Hollins, 2014; Bach et al., 2017).

For the assessment on company level so far only few approaches exist (e. g. (Duclos et al., 2010; Graedel et al., 2012; VDI Verein Deutscher Ingenieure e.V e.V, 2013; Bensch et al., 2015)), which often consider the same socio-economic limitations to availability as on product level. Additionally to availability, the vulnerability of the considered companies with regard to these materials is taken into account. Assessing the availability of materials within the context of a company's vulnerabilities is referred to as criticality. So far existing methodologies focus on abiotic resources only.

For the assessment of resource use on the country level several methodologies and studies exist (e.g. Eggert et al., 2007, Morley and Eatherley, 2008, Kind, 2011, Knašytė et al., 2012, European Commission, 2014, Bastein and Rietveld, 2015, Hatayama and Tahara, 2015, Glöser-Chahoud et al., 2016, Buchert et al., 2017 and Blengini et al., 2017). For a comprehensive assessment of resource use on the country level in the context of sustainable development, the following dimensions have to be addressed: vulnerability, availability, criticality as well as environmental and social impacts. To determine the dimension vulnerability the aspects substitutability followed by economic importance and dependency on imports are addressed most often. However, more aspects can influence vulnerability as shown by the various aspects addressed in the existing methodologies (Helbig et al., 2016).

As shown in Achzet and Helbig (2013) the most commonly applied indicators for determining the dimension socio-economic availability are concentration of reserves, production and companies as well as by-product dependency, mining capacity and demand growth. The range of considered indicators varies between one (e. g. Buchholz et al., 2012) and eight (e.g. Graedel et al., 2012).

However, studies on the product level (e.g. Schneider, 2014, Bach et al., 2016 and Henßler et al., 2016) have shown that more than these eight aspects should be established to reach a comprehensive assessment of socio-economic availability constraints. To calculate the indicator results for the socioeconomic dimension, some methodologies use global production data (e. g. Buchholz et al., 2012 and Graedel et al., 2012), while others use a mix of global production and import data, depending on the socioeconomic aspect taken into account (e.g. Erdmann et al., 2011, Knašytė et al., 2012, Hatayama and Tahara, 2015, Glöser-Chahoud et al., 2016, Buchert et al., 2017 and Blengini et al., 2017). Whereas some aspects are influenced by the global market and thus are independent from the import mix (e.g. price fluctuations), for other aspects (e.g. political stability) the import structure plays a significant role with regard to the availability of resources and raw materials and thus, should be taken into account. So far import based indicator results are only determined for the categories concentration of production and country risk (e. g. as done by Erdmann et al., 2011, Knašytė et al., 2012 and Glöser-Chahoud et al., 2016) and no comparison between import based and global results is carried out.

Next to the socio-economic availability, also the physical availability of resources should be addressed. Indicators determining the socioeconomic availability consider reserves (identified stocks from which a mineral or metal can be economically extracted as of today (United States Geological Survey, 2015)), whereas the physical availability refers to the long term availability of resources. Thus, all available resource stocks (quantified by the ultimate reserves) are taken into account, assuming that at one point in time they can be extracted as technological development progresses. Existing methodologies focus on socio-economic aspects only, whereas physical aspects are seldom taken into account.

In order to determine the final criticality of raw materials for a country, studies and methodologies either graph the availability and vulnerability dimensions together in a diagram (common two-axis assessment framework as shown by e. g. Eggert et al., 2007, Erdmann et al., 2011, Graedel et al., 2012 and European Commission, 2014) or calculate a single score results by aggregating both dimensions (as shown by e. g. Morley and Eatherley, 2008, Graedel et al., 2012, Knašytė et al., 2012, Bastein and Rietveld, 2015 and Hatayama and Tahara, 2015). So far no common agreement has been reached, which of these is the more favorable approach. However, as shown by Nassar et al. (2012) determining a single score result is challenging as weighting has to be applied, which highly influences the results.

As human beings rely on the environment (and its ecosystem services) it is defined as a resource worthy of protection (European Commission, 2005), and pollution of the environment related to resource use is taken into account in resource use assessment methodologies. Existing methodologies consider environmental implications of resource use either by evaluating pollution of the environment (as done by e.g. Buchert et al., 2017) or by applying the Environmental Performance Index (EPI) (Yale Center for Environmental Law and Policy, 2014) (as done by e.g. Graedel et al., 2012 and European Commission, 2014). When the pollution of the environment is assessed only resource specific impacts (related to resource extraction, processing use and end of life) are taken into account, whereas country specific differences, e.g. different technological standards, are not considered. When EPI is applied only the performance of a country in general and not specific for a resource is taken into account (e. g. processing of aluminum requires more energy and therefore leads to more emissions than steel (Han, 1996)). Further, country specific emissions are determined for the global production mix only, but should also be calculated for the specific import mix of the considered country. Import based results should also be compared to global averages.

Further, when determining resource use in the context of sustainable development also social aspects have to be considered (Jenkins and Yakovleva, 2006; United Nations Environment

Programme, UNEP, 2009). Social impacts of a country's resource use are so far taken into account by addressing health impacts applying life cycle impact assessment methods as done by Bensch et al. (2015) or by taken into account aspects addressed in social life cycle assessment as done by Dewulf et al. (2015) and Buchert et al. (2017), e. g violent conflicts, working conditions and corruption of the extracting country. However, country based indicators are determined only for the three countries with the highest global production, therefore neglecting countries with smaller production but possibly higher social violations. Further, social aspects should also be determined based on the import mix and results should be compared to the global average.

Most of the existing methodologies and studies address metals and minerals, with only few ones also taking into account biotic resources and raw materials (e. g. Morley and Eatherley, 2008; Kind, 2011; Knašytė et al., 2012; Oakdene Hollins, 2014) and so far only the publication by (Knašytė et al., 2012)) consider fossil fuels. Assessing availability constraints of biotic and fossil resources and raw materials and comparing them to mineral resources is relevant for a holistic assessment and to identify possible trade-offs (e. g. the use of renewable energy like wind or solar power instead of fossil energy resources leads to a higher demand of specific materials like indium, for which socio-economic availability constraints occur).

Therefore, the aim of the introduced approach is to enhance the assessment of critical resource use at the country level (SCARCE – method) by considering:

- Socio-economic availability,
    - Additional relevant categories (and corresponding indicators) are taken into account
- Environmental impacts,
    - Aspects specific for the considered resource as well as for the production country are taken into account
- Social impacts,
    - Existing indicators are improved with regard to underlying data availability and all production countries are taken into account
- Country specific results for the socio-economic availability as well as environmental and social impacts
    - The specific import mix of the country under investigation is taken into account
    - Results based on the import mix are compared to the global average
- Physical availability,
    - The long term availability of resources based on ultimate reserves is taken into account
- Vulnerability and criticality
    - Existing methodologies and frameworks are applied
- Next to metals also fossil resources.

In the next section, the overall approach to enhance the criticality assessment of a country's resource use is presented and it is shortly explained how relevant categories and indicators are identified (Section 2). Next, the individual dimensions, categories and indicators are explained in more detail (Sections 2.1–2.2) and applied in the case study of Germany (Section 3). Further, challenges of the introduced approach are discussed (Section 4) and conclusions are drawn (Section 5).

2 SCARCE method

In this section the approach to enhance the assessment of critical resource use on country level (SCARCE – method) to enhance the criticality assessment of a country's resource use is introduced. It is established to be used as a stand-alone methodology to analyze aspects of resource use in the context of sustainable development. All three sustainability dimensions are considered (see Fig. 1). The economic dimension is presented by the dimension criticality, which is assessed in the sub dimensions availability (further divided in socio-economic availability and physical availability) and vulnerability. The dimension societal acceptance is divided into the sub dimensions compliance with social standards and compliance with environmental standards, which reflect the social and environmental dimensions, respectively. For all (sub) dimensions categories and corresponding indicators are displayed. For identifying which indicators will be implemented in the introduced approach a bottom-up & top-down approach based on Bach et al. (2016) is applied (for more details see supplementary material – Section 1).

Following, the considered dimensions, sub dimensions, categories and indicators are explained in more detail.

2.1 Dimension: criticality

In this section the determination of the dimension criticality is explained. It consists of the sub dimensions availability and vulnerability, for both of which a detailed description is provided in the next sections. For evaluation of the criticality the two sub dimensions availability and vulnerability have to be evaluated first. Each sub dimension is calculated by aggregating the indicator results of all associated categories (see Fig. 1). They are then graphed within a matrix (commonly used two-axis approach), where each point represents the specific resource result of the sub dimensions (risk of supply disruption and vulnerability to this disruption). Even though several methodologies provide approaches to determine single score results, in the introduced approach the aggregation of the (sub) dimensions is not carried out. In Section 3 results for Germany are shown (see Fig. 4).

2.1.1 Sub dimension: availability

In this section the categories and indicators used to determine the sub dimension availability are introduced. The Integrated Method to Assess Resource Efficiency (hereinafter referred to as ESSENZ) developed by Bach et al. (2016) to evaluate constraints to the availability of resources and raw materials on product level within Life Cycle Assessment, is used as a basis to determine availability constraints on country level. ESSENZ provides indicators for twelve categories. The category abiotic resource depletion (based on ultimate reserves) is applied to determine the sub dimension physical availability, whereas the categories concentration of reserves and production, company concentration, price fluctuation, primary material use, mining capacity, feasibility of exploration projects, occurrence of co-production, trade barriers, political stability and demand growth are used to determine the socio-economic availability. Following, the associated indicators of these categories are introduced (Further details regarding the calculation of the indicator values can be found in the ESSENZ publication by Bach et al., 2016):

- Concentration: The categories concentration of reserves, production and companies are determined by squaring the global reserve shares, production shares and company shares respectively and summing each up individually based on Rhoades (1993).
- Price fluctuations: The category is quantified by the volatility indicator applied by German Federal Institute for Geosciences and Natural Resources (2014).
- Primary material use: To determine the effects of primary material use, the recycled content of the raw material is determined based on the data published by Graedel (2011).
- Mining capacity: To quantify this category the reserve of a raw material is set in relation to the annual production based on the data by British Geological Survey (BGS) (2014) and United States Geological Survey (USGS) 2015).

- Feasibility of exploration projects: The category is determined by multiplying the raw materials' share of global production per country with the Policy Potential Index (Cervantes et al., 2013).
- Occurrence of co-production: To quantify the occurrence of metals with regard to co-production (main or companion product) qualitative values by Angerer et al. (2009) were transformed into quantitative values.
- Trade barriers: They are measured by multiplying the raw materials' share of global production with the Enabling Trade Index (Hanouz et al., 2014).
- Demand growth: The category is quantified by calculating production increase (or decrease) over the last five years based on annual production based on data provided by BGS (2014) and USGS (2015).
- Political stability: For calculating the indicator value for this category the share of global production is multiplied by the Worldwide Governance Indicators (Kaufmann et al., 2011; World Bank Group, 2013).
- Abiotic resource depletion: For determining the category of the sub dimension physical availability the characterization factors provided by Guinée et al. (1993) and Oers et al. (2002) for ultimate reserves (crustal content) are applied. They address the quantity of a resource that is ultimately available (van Oers and Guinée, 2016). The indicator is not adapted, but scaled to 0–1.

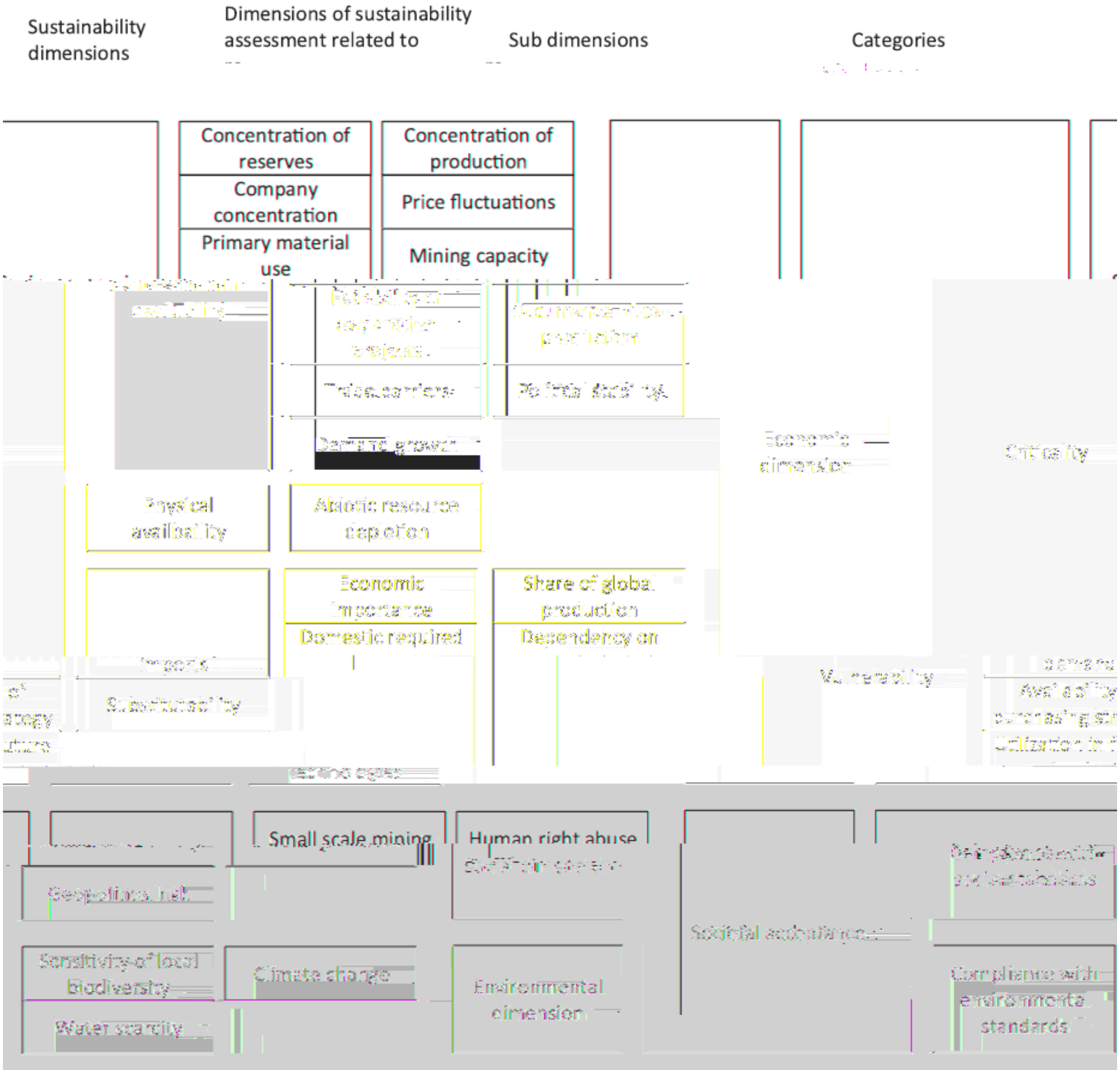

Fig. 1. Overview of considered dimensions, sub dimensions and categories considered within the SCARCE method and their link to the sustainability dimensions.

To determine the indicator results of the categories, first the indicator values have to be determined (as shown above). Then, the indicator value of a material i within a category c is set in relation to the category specific target value (an exception is the category physical availability for which no target value is available) to determine the Distance-to-Target (DtT) value based on the ecological scarcity approach (Müller-Wenk et al., 1990; Frischknecht et al., 2009) (see Eq.(1)).

$$\mathrm{DtT}\ -\ \mathrm{value}_{i,c} = \left(\frac{\text{indicator value}_{i,c}}{\text{target}_{c}}\right)^{2} \tag{1}$$

The targets were determined by a stakeholder survey within the ESSENZ project (Bach et al., 2016). The DtT - values reflect to which extent resources and raw materials face availability constraints: a value lower than 1 refers to no availability constraints (and thus is set to zero as the considered aspect does not have any potential limitation on resource availability); a value of 1 or greater than 1 refers to limited availability. Thus, the determined targets are a key element of this approach. The targets as well as a comprehensive explanation and discussion of the approach can be found in the publication by (Bach et al., 2016). Within the product oriented ESSENZ method the next steps include normalization based on global production amounts and scaling of these normalized values to 1.7 × 10 3. Finally, to determine the availability of resources and raw materials in product systems, the indicator values are multiplied with the used amount of raw materials within the product system under consideration.

The approach for the indicator values as applied in ESSENZ can also be used to adequately determine indicator values for a country assessment when the following changes are implemented:

1) Originally all six Worldwide Governance Indicator (Kaufmann et al., 2011; World Bank Group, 2013) were taken into account for the category political stability, whereas within the SCARCE method only four indicators are considered. As geopolitical risk is an aspect considered within the sub dimension availability as well as within the sub dimension compliance with social standards (see Section 2.2.2), the Worldwide Governance Indicators are divided into two sets: indicators quantifying government effectiveness, regulatory quality, rule of law and control of corruption are applied to determine availability constraints due to political stability, whereas the indicators voice & accountability and no violence are applied for the assessment of geopolitical risk (see Section 2.2.2) in the societal dimension.
2) Scale up of the raw material specific DtT - values to 0–1 instead to 1.7 × 10^{13} (for more explanation see[1]). The indicator results of a raw material i are determined by subtracting the smallest DtT – value of the category c from the original DtT - value and dividing it by the difference of the highest and smallest DtT - value. (see Eq. (2))

$$\text{indicator result}_{i,c} = \frac{\left(\mathrm{DtT} -\ \mathrm{value}_{i,c} -\ \mathrm{DtT} -\ \mathrm{value}_{min,c}\right)}{\left(\mathrm{DtT\ value}_{max,c} - \mathrm{DtT} -\ \mathrm{value}_{min,c}\right)} \tag{2}$$

3) Global production values as well as the used raw material amounts (which are considered in the availability dimension in the product assessment) are taken into account in the sub dimension vulnerability for the evaluation of the country's criticality (see Section 3.2).

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[1] The number 1.7 × 10^{13} was chosen as it presents the highest global production value of the raw material portfolio considered (Bach et al., 2016). Within the product based assessment the amount of materials are multiplied by the indicator values to determine the overall risk to availability. Since some materials can dominate the BoM on mass basis (e. g. steel in cars) (Henßler et al., 2016), the indicator values need to have a certain spreading in order to make critical materials, which are usually present in small amounts (e. g. gold in cars), visible in the results.

4) To determine availability constraints specific to a country, import data is used for the calculation of some indicators instead of global production data (see Table 1). Out of the 12 categories considered five four are not influenced by the specific import mix. Demand growth as well as price fluctuations are predominantly determined based on the global supply and demand balance rather than by exporting countries. The physical availability of a resource (defined by its amount within the earth crusts and its extraction rate) also does not depend on the countries the resources are imported from. This also applies to the categories concentration of reserves and occurrence as co-product, which are determined by the resources appearance in nature. The category primary material use is established to determine the pressure on primary materials, which can be reduced by using secondary materials. Due to missing data, the aspect cannot be determined for the considered country and is therefore included as a supply risk based on the global average recycling content of raw materials.

Table 1 Overview of indicators used to quantify availability constraints of metals and fossil raw materials.

Category	Indicator	Point of view
Demand growth	Percentage of annual growth based on past developments	Global
Concentration of reserves	Herfindahl-Hirschmann-Index (Rhoades, 1993)	Global
Price fluctuation	Volatility based on (German Federal Institute for Geosciences and Natural Resources, 2014)	Global
Physical availability	Abiotic resource depletion (Guinée et al., 1993; Oers et al., 2002)	Global
Occurrence of co-production	Percentage of production as companion metal (Angerer et al., 2009)	Global
Primary material use	Percentage of new material content (Graedel, 2011)	Global
Company concentration	Herfindahl-Hirschmann-Index (Rhoades, 1993)	Company specific[a]
Mining capacity	Reserve-to-annual-production ratio	Country specific
Feasibility of exploration projects	Policy Potential Index (Cervantes et al., 2013)	Country specific
Trade barriers	Enabling Trade Index (Hanouz et al., 2014)	Country specific
Political stability	Worldwide Governance Indicators (World Bank Group, 2013)	Country specific
Concentration of production	Herfindahl-Hirschmann-Index (Rhoades, 1993)	Country specific

[a] Due to missing data a global perspective is applied.

The other categories can be impacted by the choice of importing countries. Thus, instead of indicator values based on global production data, the import mix of the country under consideration is used as a basis for calculation. The categories trade barriers, political stability as well as feasibility of exploration projects are highly influenced by the governmental structure and practices of the exporting countries. For the category concentration of production the number of countries from which resources are imported as well as the amount of raw materials produced in these countries determine the supply risk. If raw materials are only imported from few countries with small materials amounts, the possible supply constraints are higher compared to importing them from several countries with high raw material production. This also applies to the category company concentration: being able to trade raw materials with many companies reduces possible supply restrictions, compared to being able to trade with only few companies. However, due to missing data it is not possible to calculate the company concentration for Germany or other countries (as pointed out by an asterisk in Table 1). The category mining capacity, which is quantified by the static range (reserve to annual production ratio), assess supply restrictions due to the depletion of currently operating mines and thus the need to establish new mines. As the timeframe for establishing a fully operational mine can add up to around 15 years, a raw materials might not be available in the same amounts as before and is therefore subject to potential availability constrictions. When a country imports its raw materials from countries where the mining capacity is almost exhausted, the risk of possible restrictions is higher than for raw materials imported from countries where the mining capacity is not or less exhausted.

Results based on the country specific import mix can be compared to results based on global production data to determine if the country under consideration performs better, the same or worse than the global average. To determine the difference (Δ) between the import based and global results the import based indicator result (scaled distance to target value) of the considered raw material i for category c are subtracted from the global indicator result (see Eq. (3)).

$$\Delta_{i,c} = \text{indicator result}_{\text{global,i,c}} - \text{indicator result}_{\text{import,i,c}} \tag{3}$$

Is the difference greater than zero, the global constraints are larger than for the imported materials. The constraints are equal, if the difference is zero. Is the difference lower than zero, the constraints of the imported raw materials are higher than the global average.

2.1.2 Sub dimension: vulnerability

In this section, the categories and indicators applied for the sub dimension vulnerability are introduced. The sub dimension is based on existing methodologies to determine vulnerability, in particular Erdmann et al. (2011), Buchholz et al. (2012), Graedel et al. (2012), European Commission (2014), Klinglmair et al. (2014), Oakdene Hollins (2014) and Sonnemann et al. (2015). It was ensured that only categories were selected for which data is available. Thus, the categories implemented for the assessment of a country's vulnerability are: economic importance, share of world production, internal required demand, dependency on imports, availability of purchasing strategies, substitutability, and utilization in future technologies. In Table 2 an overview of these categories and the corresponding indicators is shown. The indicators of all categories are scaled to 0–1 (see Eq. (2)) before being weighted to guarantee that comparability is possible. Aggregation of the seven categories to a single score result for every resource and raw material is necessary to plot the results within the criticality matrix.

Table 2 Overview of categories including a short description and indicator for quantification of the dimension vulnerability.

Category	Short description	Indicator
Economic importance	Economic profits of a raw materials	Value added of sectors which utilize the raw material in production according to (Knašytė et al., 2012)
Share of global production	Share of imported raw materials compared to the worldwide production	Imported amounts in relation to global production
Domestically required demand	Imported amount of raw materials	Imported amount
Dependency on imports	Domestic production	Domestic production compared to imported amounts
Availability of purchasing strategies	Purchasing strategies exist between the country under consideration with other countries	Share of the raw material imported from countries, for which purchasing strategies are established
Substitutability	Substitutability of raw materials	Share of raw material, which can be substituted
Utilization in future technologies	Demand of a specific raw material by future technologies	Share of raw material, which will be significant for future technologies

2.2 Dimension: societal acceptance

Next to availability and vulnerability also social and environmental aspects are important when assessing a country´s resource use. Both can lead to availability constraints due to low societal acceptance. Consumers are more and more interested in compliance with social as well as environmental standards (e.g. Tsurukawa and Manhart, 2011; The Guardian, 2015; Eisenhammer, 2015; Osburg et al., 2016; Aitken et al., 2016; Balanay and Halog, 2016; Wan Ahmad et al., 2016; Kemp et al., 2016) and expect companies as well as the government to uphold certain norms. Is the breach too severe, certain material cannot be imported for utilization because of possible consumer boycott. Following, the sub dimensions compliance with social and environmental standards are explained in more detail.

2.2.1 Compliance with social standards

In this section the categories and indicators for the sub dimension compliance with social standards are introduced, which are established based on ESSENZ as well as the work done by Buchert et al. (2017). Overall three aspects were identified as being significant: small scale mining, geopolitical risk and human rights abuse (see Fig. 2). These aspects are expressed as categories within the introduced SCARCE method.

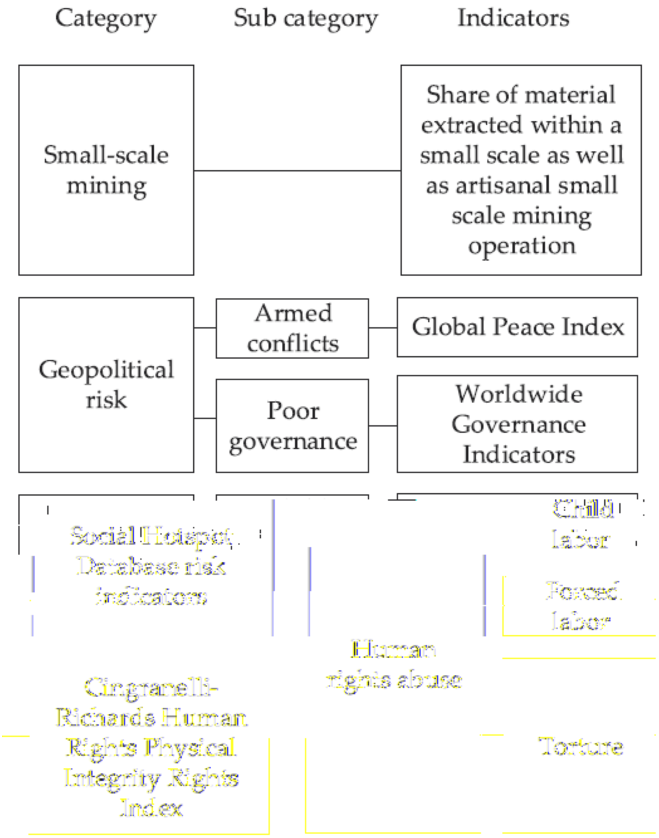

Fig. 2. Overview of considered categories, sub categories and indicators to determine compliance with social standards.

Small scale mining is one of the aspects proposed by Organisation for Economic Co-operation and Development (OECD, 2016) to identify minerals mined within risk and conflict zones. Materials mined in small scale mining operations are often used to pay for violent conflicts and wars and are characterized by poor working conditions (Lujala, 2010; Driffield et al., 2013). For quantification data regarding the global share of small scale mining operations, in relation to the considered resources, are identified (e.g. 50% of all chrome worldwide is mined in small scale mining operations) (Ghose, 2003; Dondeyne et al., 2009; Dorner et al., 2012). Furthermore, artisanal small scale mining is considered even more detrimental to human well-being than industrial small scale mining, because of its intense requirement for physical labor (Gunson and Jian, 2002). Thus, the share of materials mined in artisanal small scale mining is taken into account as an additional factor. The small scale mining indicator (SCMI), applied in the SCARCE method, is determined of a resource i by multiplying the share of the resource extracted in small scale mining operations (share of ssm) with the share extracted in artisanal small scale mining (share of artisanal ssm, which is added to 1 to prevent that the overall indicator becomes zero, when only small scale mining but no artisanal small scale mining occurs) (see Eq. (4)).

$$\mathrm{SCMI}_i = \text{ share of ssm}_i \times (\text{share of artisanal ssm}_i + 1) \tag{4}$$

The results are scaled to 0–1 according to Equation x. For resources where no data is available, it was assumed that no small scale mining takes places. As data related to small scale mining is collected for over 20 years (e.g. Brower, 1979; Godoy, 1985; Caymo, 2016) this assumption ca be seen as plausible.

Another significant parameter for compliance with social standards is countries displaying unstable governments. Within those countries the likelihood of repression of citizens (with regard to voting, freedom of expression, etc.) as well as politically motivated violence (Bienen and Gersovitz, 1986; Hafner-Burton, 2005; Jong-A-Pin, 2009) is high. To determine the category geopolitical risk two of the overall six Worldwide Governance Indicators (voice and accountability and political stability & no violence (GI) (Kaufmann et al., 2011; World Bank Group, 2013)) as well as the global peace index (GPI) (Institute for Economics and Peace, 2015) are taken into account. The GPI ranks countries regarding their level of peacefulness by considering domestic and international conflicts as well as degree of militarization (Institute for Economics and Peace, 2015).

To determine the geopolitical risk the indicators are summed up, squared (this way differences between low and high impacts are more significant), multiplied with the country specific import shares and summed up (see Eq. (5)). Results are scaled to 0–1 according to Eq. (2).

$$\text{Geopolitical risk indicator}_i = \sum \text{import shares}_{i,x} \times (\mathrm{GI}_x + \mathrm{GPI}_x)^2 \tag{5}$$

Consideration of human rights abuse is essential for determining compliance with social standards. Since small scale mining as well as geopolitical risks already take into account human rights violations, the last category focuses on additional aspects, to which consumers react especially sensitive. These aspects are child labor (CL), forced labor (FL) and overall torture (also including extrajudicial killing and political imprisonment). Child and forced labor are quantified based on data of the Social Hotspot Database (Benoit-Norris et al., 2012; Norris et al., 2013). Torture can be measured by the Cingranelli-Richards Human Rights Physical Integrity Rights Index (PIRI) (Cingranelli and Richards, 2010; Cingranelli et al., 2012). To determine the category human rights abuse for a resource i the indicators are summed up, squared (to enhance differences between low and high impacts), multiplied with the country specific import shares and summed up (see Eq. (6)). The results then are scaled to 0–1 according to Eq. (2).

$$\text{Human right abuse indicator}_i = \sum \text{import shares}_{i,x} \times (\mathrm{CL}_x + \mathrm{FL}_x + \mathrm{PIRI}_x)^2 \tag{6}$$

To determine the final result for the sub dimension compliance with social standards the three categories are summed up equally. The results are not plotted in the criticality matrix. Instead, the five raw materials with the highest risks are visually highlighted by frames with a broken line (see Fig. 4).

The indicators are calculated based on country specific import data as default. However, they can also be determined for the global production to be compared in the same way as for the sub dimension availability (see Eq. (3)). Is the difference between the global and import based results greater than zero the compliance with social

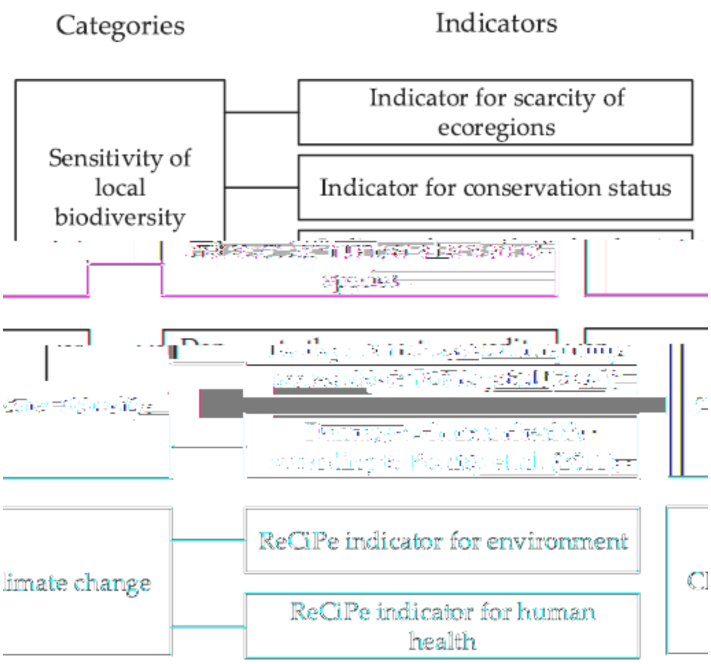

Fig. 3. Overview of categories and indicators considered for compliance with environmental standards.

standards is better for the imported materials compared to the global average. Is the difference lower than zero, the compliance is lower.

2.2.2 Compliance with environmental standards

In this section the categories and indicators for the sub dimension compliance with environmental standards are introduced. Overall three aspects are identified as relevant: sensitivity of local biodiversity, water scarcity and climate change. These aspects are expressed as categories within the SCARCE method (see Fig. 3). The state of the environment can influence the safeguard subjects ecosystem (e.g. biodiversity loss) and human health (e.g. malnutrition). Therefore, impacts on both safeguard subjects are addressed, with the exaptation of biodiversity. So far no reliable indicators exists to measure biodiversity and related ecosystem services of countries with regard to human health impacts (e. g. nutrient recycling to support food production) (Romanelli et al., 2015; Sandifer et al., 2015; Winter et al., 2017).

The sensitivity of the local biodiversity is an issue not only related to but of significance for extraction of resources mostly due to transformation of land area to mining areas including expansion of infrastructure (Pascal et al., 2008; Murguía et al., 2016). Within the SCARCE method the protection of biodiversity is quantified by using indicators as proposed in the ecoregions approach by Brethauer et al. (2013). These indicators are scarcity of ecoregions (SE), conservation status (CS) and number of endemic species (ES) and are established based on data provided by World Wildlife Fund (2012) for 827 ecoregions. These ecoregions results are converted (area weighted) into country specific indicator values.

To determine the sensitivity of local biodiversity with regard to resources i first the three indicators are scaled to 0–1, summed up and squared (to enhance differences between low and high impacts). They are further multiplied with the raw material specific import shares (see Eq. (7)).

$$\text{Impacts due to sensitivity of local biodiversity}_i = \sum\left(\text{import shares}_{i,x} \times (\mathrm{SE}_x + \mathrm{CS}_x + ES_x)^2\right) \tag{7}$$

Water scarcity is linked to severe human health issues (e.g. malnutrition (Sophocleous, 2004)) especially in developing countries as well as to impacts on ecosystems (e. g. drying up of rivers (Postel, 2000)). It is necessary for most mining operations and thus, often associated to be in direct competition with environmental and social needs (Camargo and Alonso, 2006; Vörösmarty et al., 2010; Budds and Hinojosa, 2012). Based on Pfister et al. (2009) effects on the ecosystem (expressed in potentially disappeared fractions) are determined. The method of Boulay et al. (2011) is applied to define impacts on human health (expressed in Disability-Adjusted Life Year). Both methods provide indicator values on country level, which can be set in relation to the country specific import share to determine resource i specific water scarcity impacts. Therefore, both indicators are scaled to 0–1, summed up and squared (see Eq. (8)).

$$\begin{aligned}\text{Water scarcity impacts}_i &\\ = \sum &\text{import shares}_{i,x} \\ &\times (\text{impacts on ecosystem}_x + \text{impacts on human health}_x)^2\end{aligned} \tag{8}$$

Climate change is the most addressed environmental impact worldwide (Boykoff and Yulsman, 2013; Schmidt et al., 2013; Newman, 2016) and consumers ask about the carbon footprint of their products more and more (Furlow and Knott, 2009; Upham et al., 2011). Thus, the greenhouse gas impacts of resources is also a topic of societal concern (Kolk and Pinkse, 2005; Barrett and Scott, 2012). Greenhouse gas emission data is provided in the databases of GaBi (Thinkstep, 2016) and ecoinvent (Ecoinvent, 2016) for all 40 considered materials. Country specific data is only available for some of the materials as well as countries. Thus, global averages were used to determine the resource i specific climate change impact. The impacts of greenhouse gas emissions are determined by applying the ReCiPe methodology (Huijbregts et al., 2017) to determine impacts to human health (CCHH) and the environment (CCE). The results of the two indicators are scaled to 0–1, summed up and squared (see Eq. (9)).

$$\text{Climate change impacts}_i = (\text{CCHH}_i + CCE_i)^2 \tag{9}$$

To determine the final result of the sub dimension compliance with environmental standards the three categories are summed up. The results are not plotted in the criticality matrix. Instead, the five raw materials with the highest results are visually highlighted with frames with a continuous line (see Fig. 4).

As default the indicators are determined for the country specific import mix of the considered materials. However, they can also be calculated based on global production data and compared as within the sub dimension compliance with social standards (see Eq. (3)). If the difference between the global and import based results is greater than zero the compliance with environmental standards is better for the imported materials compared to the global average. If the difference is lower than zero, the compliance with environmental standards is lower for the imported raw materials compared to the global average.

3 Case study of Germany

Next the SCARCE method is applied to the case study of Germany. First, it is shortly described how the country specific import mix is determined, then results for the individual dimension and sub dimension are presented.

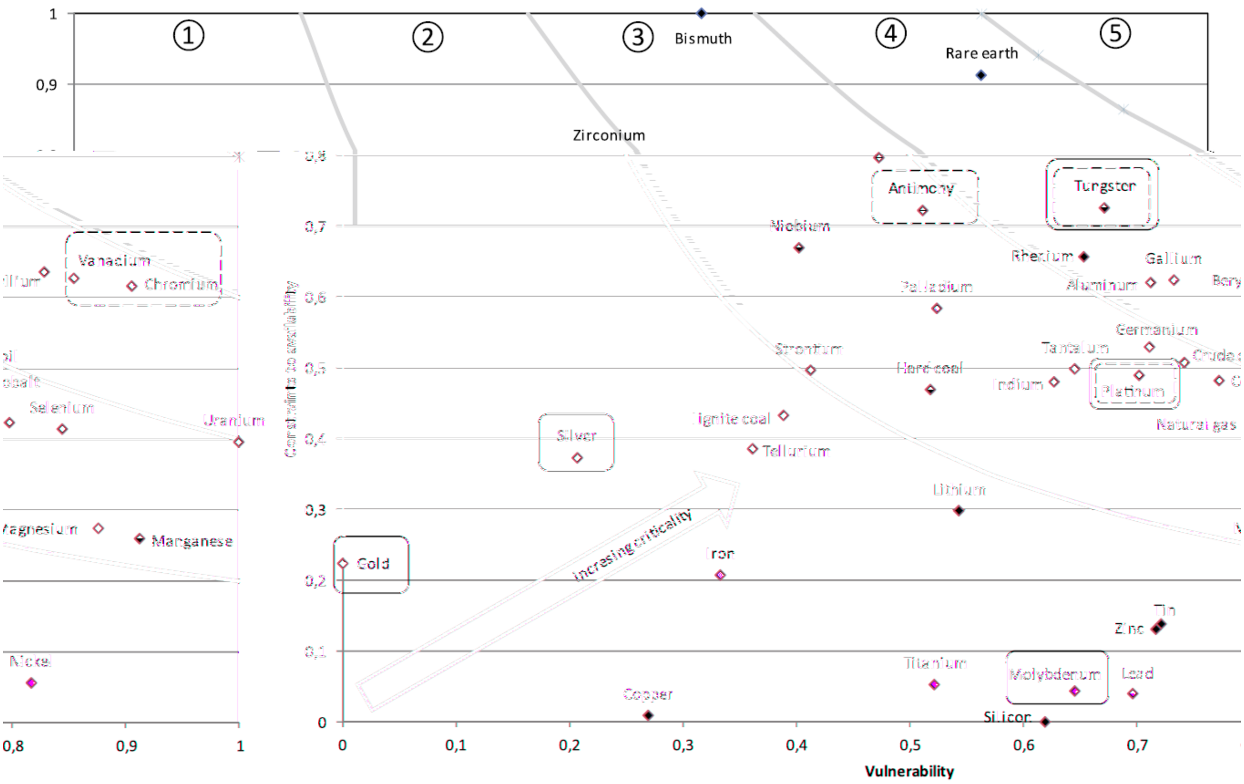

Fig. 4. Results of criticality assessment for Germany; materials with five highest values for compliance with social (frames with a broken line) and environmental standards (frames with a continuous line) are highlighted; contour lines to cluster the results in five criticality levels are shown.

3.1 Determination of the country specific import mix

In this section it is explained how the country specific import mix is determined based on data provided by Ferretti et al. (2013), BGS (2014), United Nations (2015) and USGS (2015). The country specific import mix shall reflect from which fossil raw material and ore producing countries Germany imports raw materials (in the following the term ore is used to refer to metal ores as well as fossil raw materials). Even though data by United Nations (2015) provides import data for Germany based on current trade statistics, some materials imported into Germany are first traded to other European countries and then imported to Germany. For some materials this makes it impossible to trace the original producing countries (e.g. according to the provided data all gold used in Germany is imported from Switzerland; however within Switzerland no gold is mined). Thus, the import data is corrected using production data by BGS (2014) and USGS (2015). Import statistics and production statistics are compared for every raw material. When all countries importing a raw material into Germany are also producing the raw material, the country specific import mix can be used without adaptation. In case the countries in the import mix are not producing the raw material, the import mix is adapted accordingly as follows. When only few of the exporting countries are not ore producing countries, the overall amount of these countries is allocated to the producing countries based on the global production shares. When none of the exporting countries are producing the ore, the import mix is set equal to the global production mix. Finally, as for some materials purchasing strategies exists (see Section 3.3.2) (e.g. natural gas imported from Kazakhstan (Ferretti et al., 2013)) the country specific import mix is adopted accordingly (e. g. the import share of natural gas from Kazakhstan is set to 17% independently of the import data and global production). The determined import mix thus only covers the import of raw materials but not of products or intermediate products (e.g. metal plates).

3.2 Overall result for Germany

In this section, the overall result for the case study Germany is shown including aggregated results of all four (sub) dimensions (see Sections 3.3.1–3.3.3).

In Fig. 4 the criticality matrix for Germany is displayed showing aggregated results of the raw materials for the dimensions availability and vulnerability. The materials with the five highest results for the dimension societal acceptance are highlighted. Frames with broken lines are used for the category compliance with social standards, whereas continuous lines are used for the category compliance with environmental standards. To support the interpretation of the results contour lines based on approach by Glöser et al. (2015) are displayed. As the criticality matrix is linearly scaled, the contour lines have a convex shape. By adding contour lines to the criticality matrix, the considered raw materials can be clustered in five areas representing different levels of criticality. Raw materials within level 1 can be seen as least critical, whereas raw materials in level 5 show the highest criticality.

As shown in Fig. 4 none of the considered raw materials has a criticality level of five. The materials with the highest criticality are rare earth metals, which are the only raw materials in level 4. Further, bismuth, tungsten, rhenium, aluminum, gallium, beryllium, vanadium und chromium are classified with a criticality level of 3. Chromium, vanadium and tungsten also have a high risk to be not compliant with social standards (see Section 3.3.3.1 for more details). Tungsten even shows a high risk to violate environmental standards (see Section 3.3.3.2 for more details). Antinomy and platinum, which are classified with a level 2 criticality, are also associated with noncompliance of social standards; platinum even with the noncompliance of environmental standards. Gold, silver and molybdenum, which are classified with the criticality level of 1, are associated with noncompliance of environmental standards. Based on these results, the raw materials rare earth, tungsten, vanadium and chromium are the three materials, which should be further analyzed regarding reducing their criticality as well as social and environmental implications.

3.3 Results of individual dimensions

Next the results for the individual dimension (availability – Section 3.3.1; vulnerability – Section 3.3.2; compliance with social standards – Section 3.3.3.1; compliance with environmental standards – Section 3.3.3.2) are introduced in more detail to explain the overall result presented in Fig. 4.

3.3.1 Results of sub dimension availability

In this section the result of the sub dimension availability is analyzed in more detail. As shown in Fig. 5 the raw materials silicon, copper, lead, molybdenum und titanium have the lowest risk regarding constraints to availability, whereas bismuth, rare earth, zirconium, tungsten and crude oil are the materials with the highest risks.

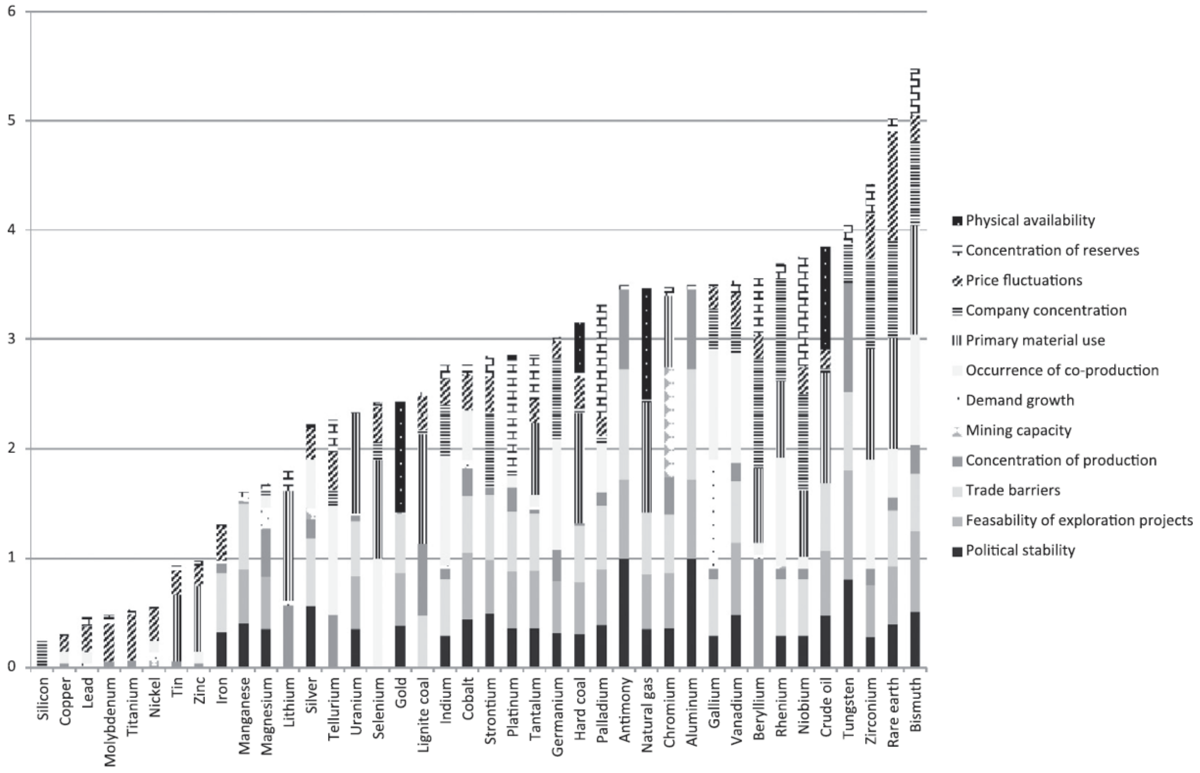

Fig. 5. Result of sub dimension availability.

Following, the results for bismuth are explained exemplary in more detail. For bismuth the categories with the highest risks are occurrence of co-production and primary material use. As bismuth is only mined as a by-product of lead, copper and other metals (Campbell, 1985; Ayres et al., 2003) the associated risk for the category occurrence of coproduction is plausible. It is used as an alloy metal as well as an substance in pharmaceuticals and as a pigment for cosmetics and paints (Anderson, 2014). So far only the share used as an alloy metal can be recycled. Thus, the overall recycling rate is low summing up to a recycled content of around 10% (Graedel et al., 2011). This explains the high potential availability constraints associated with this category. Additionally bismuth shows high risks for four more categories (company concentration, trade barriers, political stability and feasibility of mining operations). Overall only for three categories (physical availability, demand growth and mining capacity) there are no associated possible availability constraints. A detailed analysis like shown for bismuth should be carried out for all or at least the raw materials with the highest possible availability constraints.

The categories primary material use, trade barriers and political stability have the highest risk for most raw materials. Low recycling rates for several of the raw materials especially ones used in electronic devices (Graedel, 2011) explain the high risks for the category primary material use. Even though there is no direct correlation between trade barriers and political stability, often both categories are influenced by the country's politics. Studies have shown that even though political stability can be a cause for decreasing trade barriers, the correlation cannot be applied for all countries (Enowbi Batuo and Asongu, 2015; Bonnal and Yaya, 2015; Puig and Chan, 2016). Thus, it is adequate to consider both categories, keeping in mind that similar results are plausible. As Germany has to import almost all of its resources (Huy et al., 2014), it relies on resource rich countries. Several of these resource rich countries are characterized by governments struggling to establish strong governmental institutions (Gylfason, 2001; Hodler, 2006; Venables, 2016; Siakwah, 2017) leading to low political stability and thus often high trade barriers (also called ”resource curse”).

The categories demand growth, mining capacity and physical availability have a low influence with regard to availability constraints for most raw materials. For most raw materials demand growth has not been above average in the last years. Future trends (e.g. e mobility) which could increase the demand of specific raw materials are considered in the sub dimension vulnerability (Section 3.3.2). The mining operations of the countries from which Germany imports its raw materials are set up to last longer than 50 years and thus do not display any risk with regard to possible availability constraints. The physical availability refers to the total amount of an element in the Earth's crust regardless whether it is economically and technically extractable today or most likely in the future. Thus, the amount characterized as available is very high for the most raw materials and the category only plays a role for natural gas, tungsten, gold and hard coal as these materials show comparably low natural deposits.

As addressed in Section 2.1.1 the results of the import-based categories (political stability, trade barriers, concentration of production, mining capacity and feasibility of mining operations) can be compared to the global results (see Fig. 6). Raw materials with values higher than zero have a lower risk with regard to availability constraints compared to the global average. The overall result is marked with a black rhombus sign. For Germany lead performs much better than the global average especially in the categories feasibility of exploration projects, trade barriers and political stability. China is with 50% the main global producer of lead BGS (2014) and USGS (2015). Its mining industry is characterized by i. a. challenges related to infrastructure, community development conditions as well availability of a sufficient geological database for better exploration strategies. China currently holds the 54th place (out of 104) with regard to attractive jurisdiction (Wederman, 2004; Cervantes et al., 2013). Germany imports only 6% of its lead from China. Most supplies are shipped from Australia, Sweden and USA (United Nations, 2015; USGS 2015), for which the policy potential index (indicator which quantifies the category) performs well. The high global production shares of China and the low amount imported by Germany are also the reason for a better performance of the category trade barriers and political stability.

Raw materials with a value lower than zero have a higher risk of availability constraints than the global average. For Germany the highest risks compared to the global average occur with regard to aluminum for the categories political stability and concentration of production.

According to United Nations (2015) Germany imports 92% of its aluminum from Guinea. The country is characterized by political upheaval (Hall, 2015; Dhillon and Kelly, 2015) and is therefore political unstable. From a global perspective Guinea only produces 6% of the global amount of aluminum, 30% is produced in Australia, 19% in Indonesia and 17% in China. These countries have lower worldwide government indicator values (indicator quantifying political stability) as Guinea. The large amount of aluminum imported from Guinea also explains the high concentration of production for the import mix, whereas on global level several countries contribute to aluminum production (BGS, 2014).

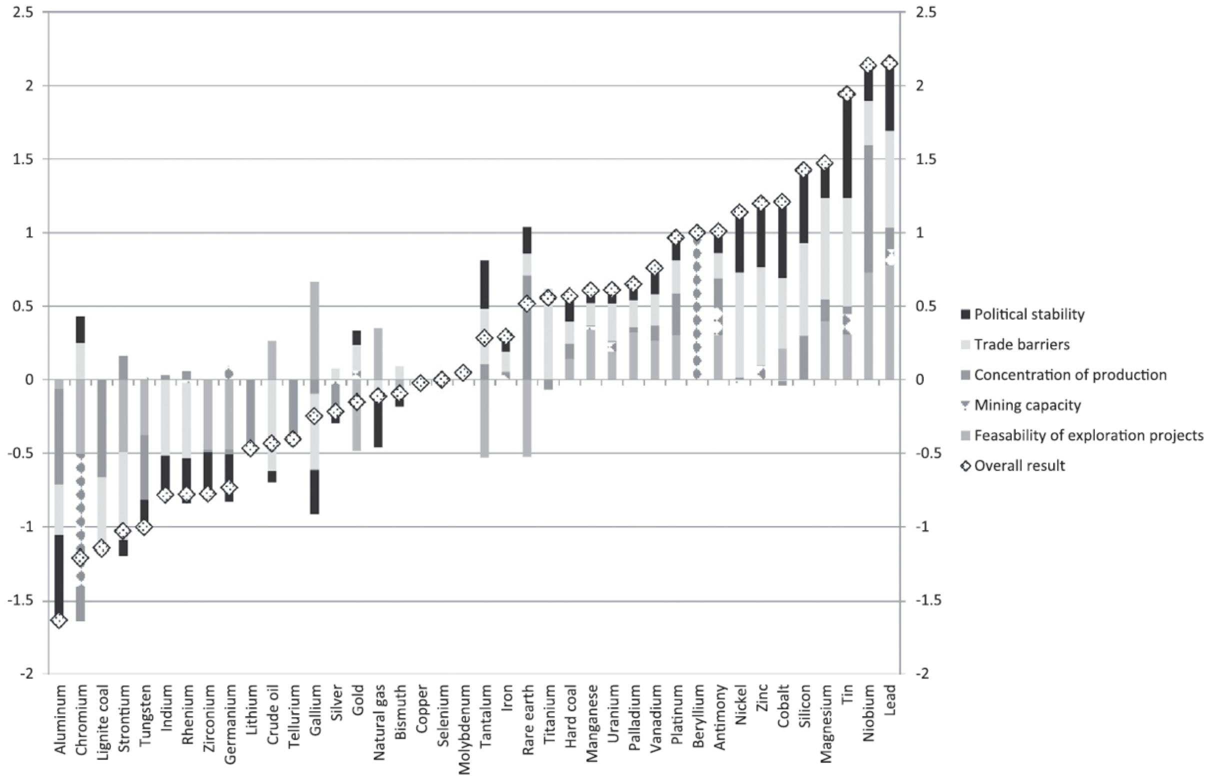

Fig. 6. Comparison of the import based and global results for the categories political stability, trade barriers, concentration of production, mining capacity and feasibility of mining operations.

3.3.2 Results of sub dimension vulnerability

In this section, it is shortly described how the categories are quantified for the case study of Germany. Then the results of the sub dimension are shown and explained.

For the categories utilization in future technologies and substitutability data by Erdmann et al. (2011) is used. Within this publication substitutability and utilization in future technologies of raw materials for the German market are assessed and clustered into values from 0 to 1. Thus, these values can be adopted without being converted. As shown in Table 2 the quantification of the category domestically required demand is achieved by scaling the imported amounts based on BGS (2014) and USGS (2015) to values from 0 to 1 (1 represents the highest imported amount). The imported amounts are set in relation to the global production to quantify the category share of global production. Dependency on imports is identified by determining the amounts of material produced within Germany based on Huy et al. (2014) and comparing them to the imports. To quantify the influence of availability of purchasing strategies it is determined how big the import shares are regarding countries for which these strategies exists (Ferretti et al., 2013). The share is subtracted from 1, leading to values from 0 to 1. The economic importance of a material is determined based on the added value to German companies utilizing the raw material based on data by Statistisches Bundesamt (2012, 2015) (Federal Statistical Office). The final results of the categories are scaled to 0–1.

The results of the individual categories are aggregated as shown in Fig. 7. The results of the sub dimension vulnerability are analyzed in more detail. Germany shows the lowest vulnerability with regard to gold, silver, copper, iron and tellurium. Uranium has the highest vulnerability followed by manganese, chromium, magnesium and vanadium. Exemplary the results for uranium are analyzed in more detail. Such a detailed analysis should be carried out for all or at least the raw materials with the highest vulnerability.

For uranium the category share of global production has the highest results. Even with the Nuclear Phase-Out Act (Gesetz zur Änderung des Atomgesetz (Deutscher Bundestag, 2011)(German parliament) Germany still relies on energy from nuclear power for its electricity, leading up to a share of about 14% nuclear energy (de Menezes and Houllier, 2015; Arbeitsgemeinschaft Energiebilanzen, 2016 (Working Group on Energy Balances)). As Germany only has small amounts of uranium resources, which are currently not extracted, they have to import uranium – 1890 t in 2015 (Statista, 2015). Therefore, the category share of global production (imported amount in relation to world production) is the category with the highest contribution. Furthermore, the category economic importance shows also high results, since uranium is utilized in the energy sector which generates a high value added (Statistisches Bundesamt, 2012, 2015). Other important categories are dependency on imports (due to absence of domestically resources) and availability of purchasing strategies (no purchasing strategies for uranium exist in Germany (Ferretti et al., 2013)). However, it can be assumed that the dependency on uranium will decrease significantly in the next years due to the Nuclear PhaseOut Act.

The results of the sub dimension availability and vulnerability are plotted in a diagram – the criticality matrix (as shown in Fig. 4). The results of both sub dimensions have to be considered to determine the criticality of a raw material. For example, even though the vulnerability of uranium is high, its risk with regard to availability constraints is rather low.

3.3.3 Results of dimension societal acceptance

The dimension societal acceptance consists of the two sub dimensions compliance with social standards and compliance with environmental standards. For both sub dimensions the overall results are presented. Further, the import based results are compared to the global production shares to determine if raw materials imported to Germany perform better or worse than the global average.

3.3.3.1 Results of sub dimension compliance with social standards.

In this section, the results of the sub dimension compliance with social standards are explained in more detail. As shown in Fig. 8 lignite coal, tellurium, lithium, beryllium and zinc have the highest compliance with social standards (and therefore low indicator values).

Chromium, antimony, platinum, vanadium and tungsten have the lowest compliance with social standards (and therefore high indicator values). For tungsten the category small scale mining has the highest impact as it is predominately imported from Bolivia (United Nations, 2015), where small scale mining operations are responsible for almost all tungsten extraction (Noetstaller, 1987; Hilson, 2002). For antimony the impact of small scale mining is high since it is predominantly imported from China, where it is most likely extracted within small scale mining operations (Noetstaller, 1987; Gunson and Jian, 2002; Shen and Gunson, 2006). Chromium, platinum and vanadium are prominently imported from South Africa, Russia and China – countries where human right violations and political conflicts occur (Seedat et al., 2009; Cingranelli et al., 2012; World Bank Group, 2013; Human Rights Watch, 2016). Thus, the results for these categories are high.

Further, the import based results are compared with the global results to analyze for which raw materials Germany performs better or worse than the global average. As shown in Fig. 9 Germany shows better results for the raw materials silicon, lead, rare earth, zinc and tantalum.

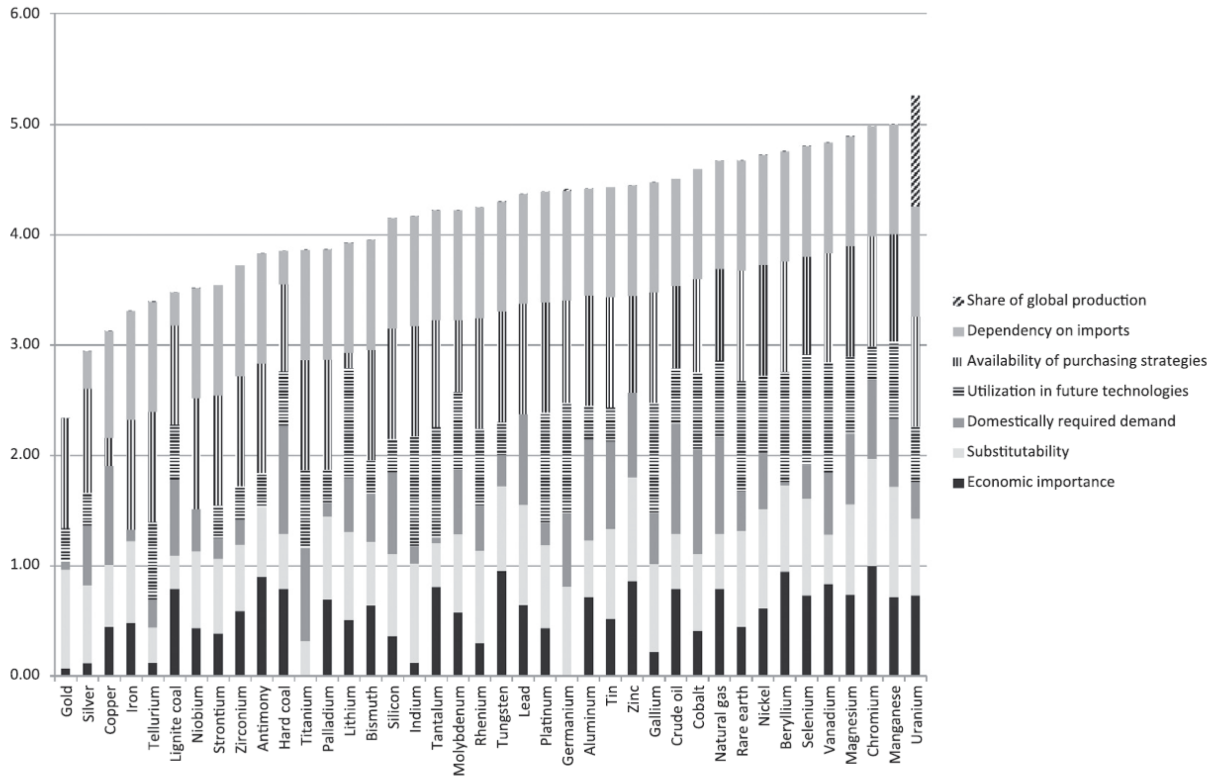

Fig. 7. Results of the sub dimension vulnerability.

For silicon the categories human right abuse and geopolitical risk perform better than the global average. Germany imports its silicon mostly from Norway, Poland and France, where human right abuse as well as the geopolitical risk are small. Globally China and Russia are the biggest producer, which have comparably higher risk with regard to the considered categories.

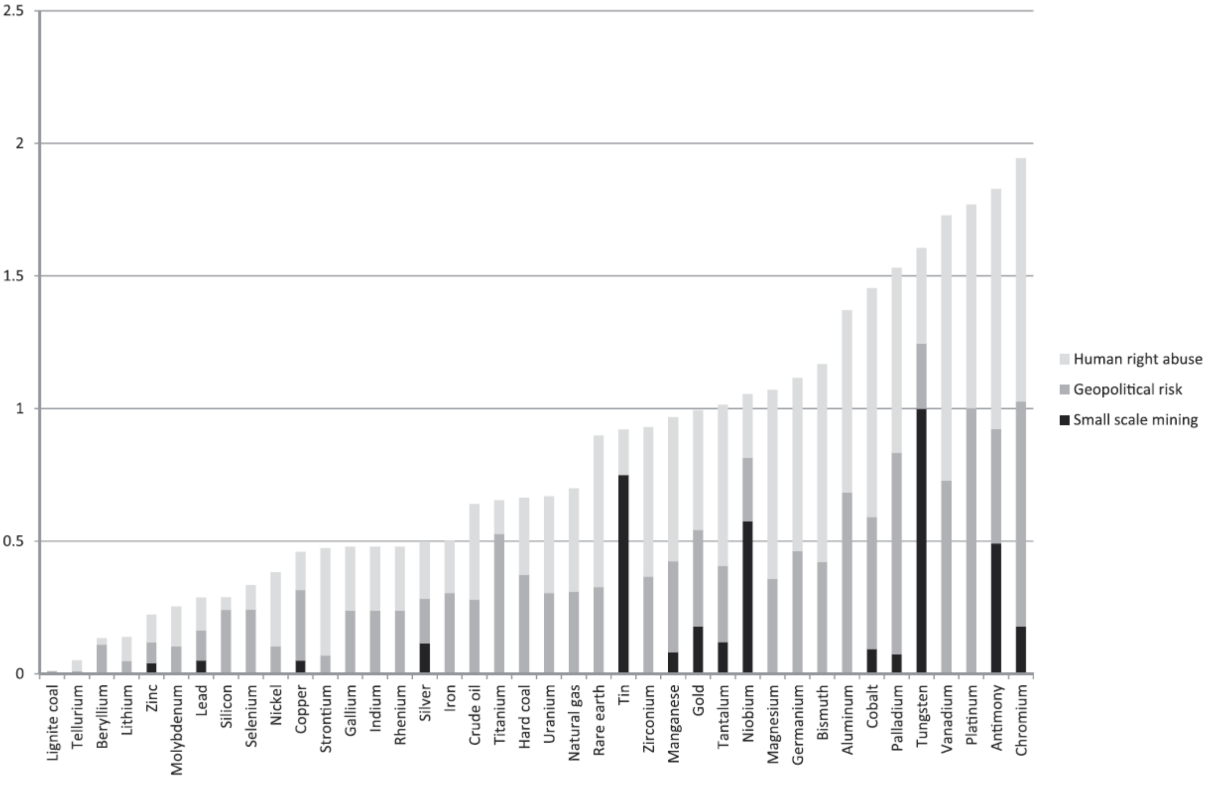

Fig. 8. Results for the sub dimension compliance with social standards.

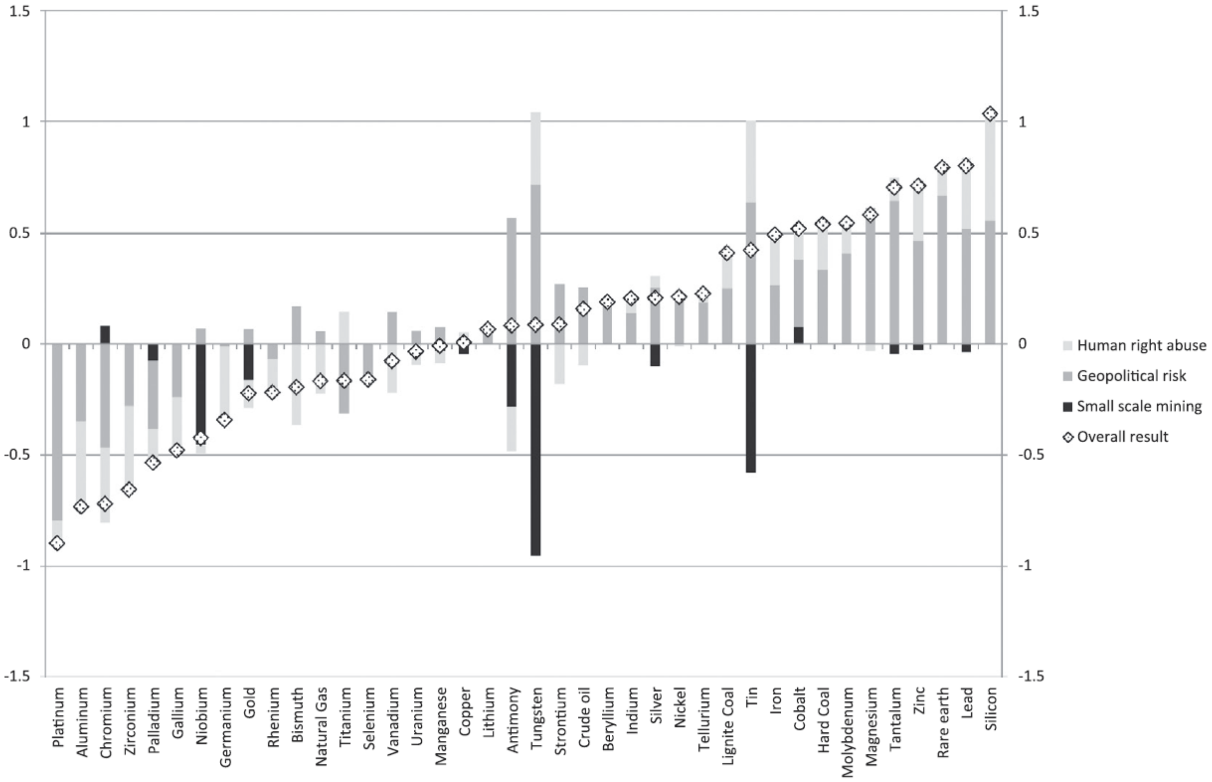

Fig. 9. Comparison of the import based and global results for the sub dimension compliance with social standards.

Tin and tungsten perform worse than the global average for the category small scale mining. As described above tungsten is imported predominantly from Bolivia, whereas from a global point of view not all tungsten is extracted within small scale mining. The same applies for tin: it is imported from Thailand and Peru (both countries are associated with small scale mining (Noetstaller, 1987; Labonne, 1996; Hentschel et al., 2002)), whereas globally only a small amount is extracted within small scale mining operations (Dorner et al., 2012). Platinum, aluminum and chromium also perform worse compared to the global average for the categories geopolitical risk. This can also be explained by the import mix: aluminum is predominantly imported from Guinea, whereas in the global production mix Guineas share is rather small and large amounts are produced in Australia (with 30%), China (with 18%) and Indonesia (with 19%) (USGS, 2015). As already explained, Guinea has been dealing with by political upheaval in recent years (Hall, 2015; Dhillon and Kelly, 2015) also leading to human rights violations (Human Rights Watch, 2016).

As addressed above imported chromium is predominantly mined in South Africa (a county where human right violations and political conflicts occur (Kynoch, 2005; Seedat et al., 2009)) and therefore performs worse than the global average, where the share extracted in South Africa is much smaller. The imported zirconium comes to 60% from China (and 14% from USA as well as 15% from Australia), whereas for the global production mix Australia is the country with the highest production share (50%; further 10% in USA and only 3% in China). As human right abuses occur in China (Lee, 2007; O'Brien, 2015; Pedersen and Kinley, 2016) a higher imported amount results in a higher difference of the result.

3.3.3.2 Results of sub dimension compliance with environmental standards.

Following the results for the sub dimension compliance with environmental standards are explained. As shown in Fig. 10 tellurium, lignite coal, aluminum, selenium and lithium perform best, whereas gold, tungsten, platinum, silver and chromium perform worse. Overall the category climate change has only an influence on few raw materials: gold, platinum and palladium. Studies as well as current databases show that the climate change impact of these raw materials is especially high (Norgate et al., 2007; Nuss and Eckelman, 2014; Ecoinvent, 2016; Thinkstep, 2016). The high climate change impacts of gold and platinum can be explained by the high energy use for extraction due to their low ore grades (Mudd, 2007; Yang, 2009).

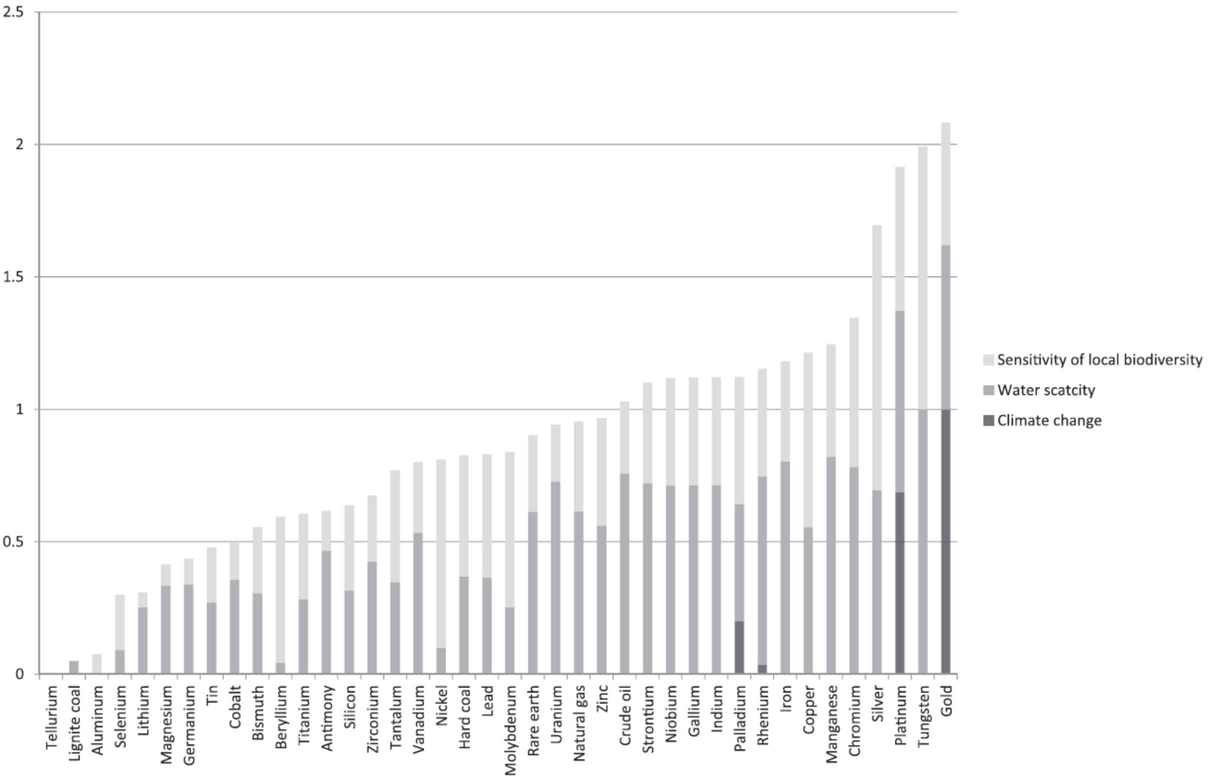

Fig. 10. Results for the sub dimension compliance with environmental standards.

The results for water scarcity and sensitivity of local biodiversity are determined country specific. The category water scarcity is very high for tungsten as it is mined in Bolivia. Even though Bolivia is characterized as a country with medium water scarcity from a resource perspective (Berger et al., 2014), due to governmental regulations and low state of the art with regard to drinking water and wastewater treatment technology in rural areas risks related to human health exists (Spronk and Webber, 2007; Wutich and Ragsdale, 2008; Calizaya et al., 2010).

Silver shows the highest sensitivity with regard to the local biodiversity, because almost 50% of silver is imported from Argentina. Argentina is one of the most biodiverse countries in the world with several areas under protection. However, the transformation of ecosystems to agricultural areas, logging activities and oil and gas prospecting have increased in recent years. Thus, the amount of mammals, amphibians and birds listed under a category of threat has been growing as well (Grau and Diego Brown, 2000; Manrique et al., 2013; Secretariat of the Convention on Biological Diversity, 2014a).

Further, the import based results are compared to the global results to analyze for which raw materials Germany performs better or worse than the global average. As shown in Fig. 11 only for few materials Germany performs better than the global average, for most raw materials it performs worse. The overall result is marked with a black rhombus sign. Climate change is zero for all raw materials as the results are not influenced by import mixes, but are established on a global level.

Especially for tungsten and silver the imported raw materials perform worse. This can be explained by the import structure. As already mentioned silver is mostly imported from Argentina which has a high sensitivity with regard to the local biodiversity. On a global scale overall 58 countries mine silver worldwide with individual production shares around 14% (BGS, 2014). Due to this high amount of countries mining silver including many countries with low sensitivity of the local biodiversity the global average is smaller than the import based result. Tungsten is predominantly imported from Bolivia, which has a high sensitivity with regard to the local biodiversity (Finer et al., 2008; Secretariat of the Convention on Biological Diversity, 2014b).

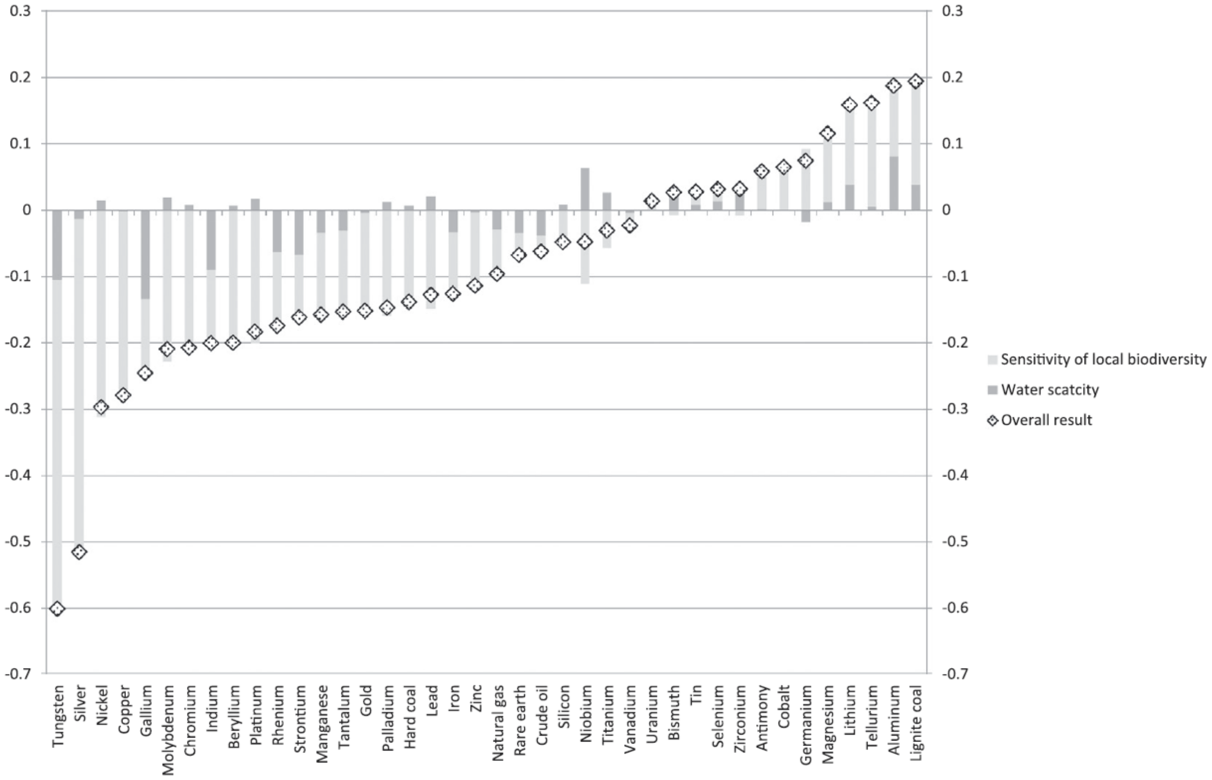

Fig. 11. Comparison of the import based and global results for the sub dimension compliance with environmental standards.

Considering global production Bolivia has a small share of 2% and most of the tungsten is mined in China (80%) and Russia (10%) (BGS, 2014; USGS 2015). The sensitivity of the local biodiversity is smaller in China than in Bolivia, because of its smaller biodiversity richness and its higher overall conservation status (based on current trends and conditions) (World Wildlife Fund, 2012).

4 Results and discussion

The aim of the introduced SCARCE method is to provide an improved criticality assessment by considering a comprehensive set of availability indicators, and determine them based on the individual country specific import mix of countries instead of the global production mix. Furthermore, the criticality framework is expanded to include social and environmental aspects and achieve a first step towards sustainability assessment for resources.

Indicator values based on global production are provided for the categories of the sub dimensions availability, compliance with social standards and compliance with environmental standards for all 40 considered resources and raw materials. Further, the indicator values on country level are provided for the dimension societal acceptance. They can be used to calculate import based results for this dimension (data are provided within the supplementary material – Section 2). Providing data enhances the applicability of the SCARCE method tremendously.

The SCARCE method is applied on a case study of Germany. The plausibility of results could be shown. However, several challenges exist which are addressed and discussed in the following.

Within all sub dimension aggregation occurs to determine a single score reflecting the corresponding (sub) dimension. This means the twelve categories of the sub dimension availability, the seven categories of the sub dimension vulnerability as well as the three categories (and the corresponding indicators within the categories) of the sub dimension compliance with social standards and the three categories (as well as the corresponding indicators of the categories) of the sub dimension compliance with environmental standards are aggregated to one value respectively. For all sub categories equal weighting of all categories (and indicators) is applied as proposed in existing methodologies (e. g. Erdmann et al., 2011, Graedel et al., 2012, VDI (2013), European Commission, 2014 and Bach et al., 2016). As weighting is always subjective (Finkbeiner et al., 2014) it has to be kept in mind that the results could change if different weighting factors are applied. Further, due to the unequal amount of indicators and categories considered within the dimensions, an implicitly weighting occurs. For example, in the sub dimension availability overall 12 categories are considered, whereas in the sub dimension vulnerability only seven categories are taken into account. Thus, the individual categories of the sub dimension vulnerability contribute more to the overall result of this sub dimension. Whereas the individual categories of the sub dimension availability contribute comparably less to the overall result of the sub dimension availability. However, if interpretation of the results is followed as proposed (as shown in the case study for Germany), each category and dimension including the applied weighing schemes should be adequately reflected and can therefore be taken into consideration during interpretation and formulation of possible policy options. Further, none of the proposed approaches to determine a single-score result for criticality was applied due to the uncertainties associated with weighting. Nassar et al. (2012) showed that single score results for criticality vary significantly depending on the weighting approach applied. Thus, the aggregation to one criticality results provides limited additional value for the interpretation of the results.

All indicators applied in the SCARCE method face the challenge of underlying data quality. If the data quality is poor, higher uncertainties are associated with the indicator results. More established indicators (e.g. Enabling Trade Index (Hanouz et al., 2014)) tend to have lower uncertainties because they are improved over time. Further, data for calculating the import mix, global production as well as the indicator values are derived from different years (data used originates from the years 2010–2016).

Furthermore, so far the SCARCE method has only been applied for imported raw materials but does not take into account intermediate products (e.g. metal sheets) and final products (e.g. automotive battery), which can be influenced by availability constraints, vulnerability and societal acceptance as well (Peiró et al., 2013; Lapko et al., 2016).

To fully assess the availability of primary materials anthropogenic stocks have to be taken into account as they can lower the pressure on primary materials. No data with regard to anthropogenic material flows is currently available for Germany (it is assumed this is also the case for most other countries) (Zimmermann and Gößling-Reisemann, 2013; Schiller et al., 2015; United Nations, 2015). Thus, this aspect could not be included in the assessment. To consider this aspect at least to some extent the recycled content was included within the availability assessment. Additionally, the assessment can only be applied to primary materials. The criticality of secondary materials cannot be quantified due to missing data on international and national recycling markets for all considered materials. However, the identified categories and indicators could mostly be applied for secondary materials if sufficient market data were available.

For the sub dimensions compliance with social and environmental standards data on country (and sector) level is applied. Thus, no statement with regard to the status of specific mines can be made, because so far there are no indicators and data available. One important aspect missing in the sub dimension compliance with environmental standards is the occurrence of accidents during mining operation, e.g. leaking tailing ponds (Howard, 2015; Schoenberger, 2016). However, no data is available for such accidents on global level yet. Therefore, it is currently not possible to quantify them. Further, climate change impacts were determined based on global data provided by GaBi and ecoinvent. Therefore, different technologies within different countries are not taken into account. To redefine this aspect, country specific technologies should be analyzed so that specific inventory data can be derived.

The results for the category mining capacity are determined based on import data, considering the depletion of current mines in the specific countries from which imports occur. However, it could also be argued, that the global market will compensate depleted mines by newly developed ones and thus, that the category should rather be determined on a global level. At this point, it is not known, how and if the global market will balance out country specific mining capacities. As the import mix is compared with the global average, both results are determined and can be analyzed. As shown in Fig. 6 differences between import based and global average results are only significant for few raw materials.

The worldwide governance indicators are applied to determine the political stability within the sub dimension availability as well as for the geopolitical risk for the sub dimension compliance with social standards. Even though different indicators are used (see Sections 2.1.1 and 2.2.1) and no direct correlation occurs between these two indicator sets (see supplementary material – Section 3), often the same resources and raw materials are being quantified as having a high or respectively low risk. Thus, it should be further analyzed if one of the indicator sets could be excluded to limit the overall amount of considered indicators and categories.

Further, the Abiotic Resource Depletion indicator (Guinée et al., 1993; Oers et al., 2002) using ultimate reserves (crustal content) as a basis is applied to determine the physical availability of resources. As the ultimate reserves can never be extracted completely, because some stocks will always remain unavailable under all foreseeable conditions, using the ultimate reserves as a basis to determine the physical availability of resources leads to an overestimation of available resources. However, the ultimate reserves has been evaluated as the most stable and comprehensive dataset and is applied to determine the resource depletion within life cycle assessment case studies (Drielsma et al., 2016; van Oers and Guinée, 2016).

5 Conclusion

The SCARCE method enhances the criticality assessment of a country's resource. By establishing the new dimension societal acceptance social and environmental aspects are taken into account. Additionally next to metals also fossil fuels are considered, which can directly be compared to metals. This is especially important when systems are compared where fossil energy sources are replaced by renewable systems which require high amounts of certain metals (e.g. lithium and tellurium for solar energy power). Another feature of the SCARCE method is the possibility to determine certain socio-economic availability aspects (e.g. political stability) based on the specific import situation of a country. These country specific results can be compared with results determined based on the global production mix to determine if the country under consideration performs better or worse than the global average. Finally by considering additional categories for the sub dimension availability, which have not been taken into account so far (e.g. feasibility of exploration projects), the evaluation of socioeconomic constraints to resources is improved. Thus, the SCARCE method goes beyond existing methodologies and considers the use of resources in the context of sustainable development.

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